



# Virtual Seismometers for Induced Seismicity Monitoring

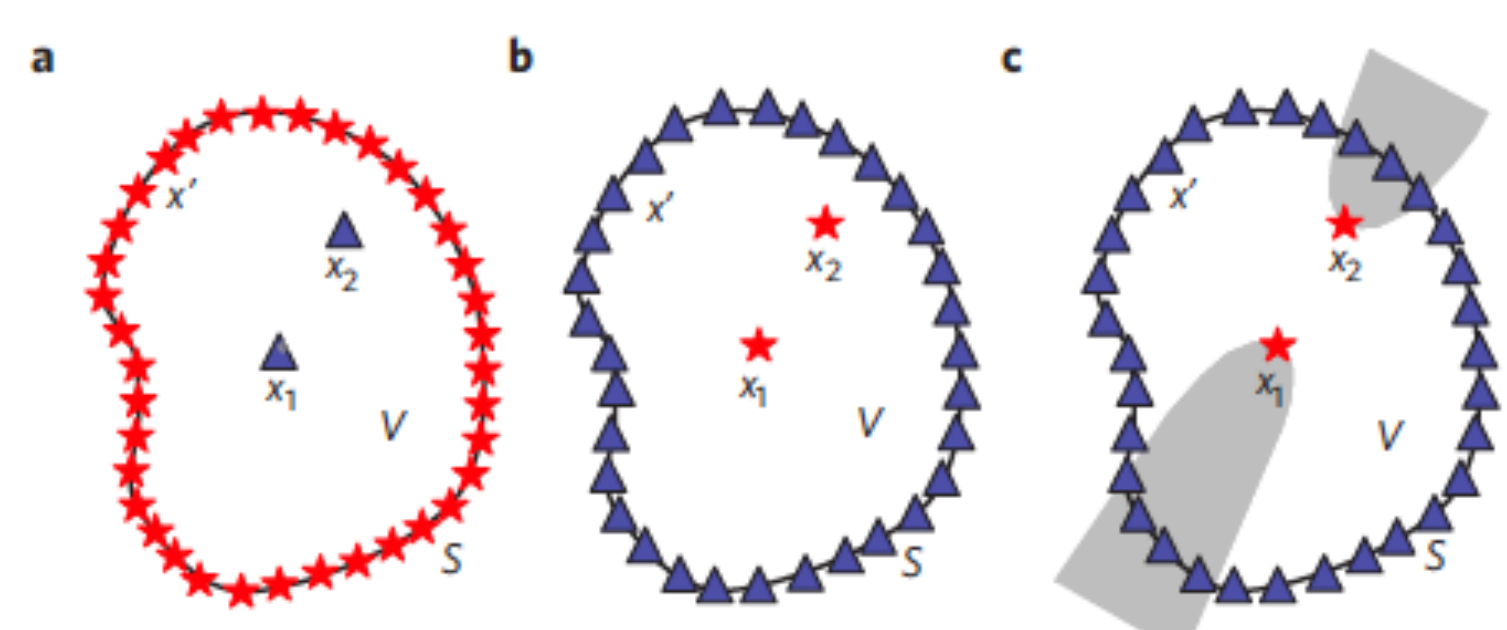
Christina Morency and Eric Matzel  
Lawrence Livermore National Laboratory, Livermore, CA, US

## Abstract

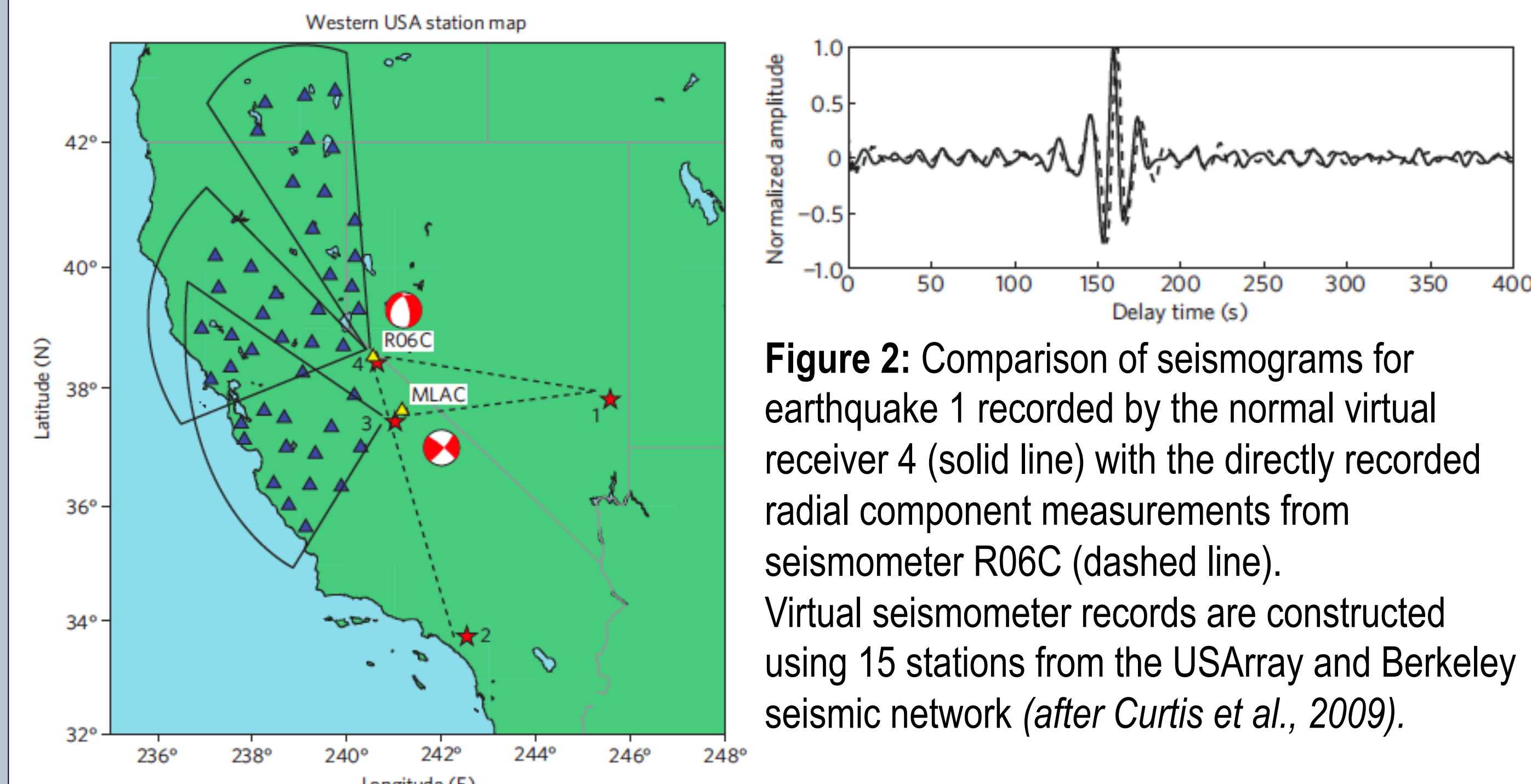
Induced seismicity is associated with subsurface fluid injection, and puts at risk efforts to develop geologic carbon sequestration and enhanced geothermal systems (EGS). We are researching methods to monitor microseismically active zone so that we can identify faults at risk of slipping. We are using the Virtual Seismometer Method (VSM), which is an interferometric technique that is very sensitive to the source parameters (location, mechanism and magnitude) and to the earth structure in the source region. Given an ideal geometry, when two quakes are roughly in line with a recording station, the correlation of their waveforms provides a precise estimate of the Green's function between them, modified by their source mechanisms. When measuring microseismicity, this geometry is rarely ideal and we need to account for variations in the geometry as well. Thanks to VSM, we can focus on properties directly between induced micro events, and doing so, monitor the evolution of the seismicity and precisely image potential fault zones. Here, we show that the cross-correlated signals recorded at the surface are a combination of the strain field between two sources times a moment tensor. Based on this relationship, we are investigating the feasibility to use this measured cross-correlated signal to invert for focal mechanism.

## Virtual Seismometer Method

Whereas seismic interferometry has been mainly used to transform a seismic sensor into a virtual source (e.g., Campillo and Paul, 2003), Curtis et al. (2009) have developed a theory based on reciprocity to **turn earthquake sources into virtual seismometers** (Fig. 1). This latter allows to derive the Green's function between two earthquakes, as if one of these earthquakes had recorded the signal emitted by the other (Fig. 2).



**Figure 1:** Sketch of source-receiver geometries used for seismic interferometric methods. **a.** Cross correlation of the signal recorded at the receivers  $x_1$  and  $x_2$ , emitted from the sources  $x'$  located on the surface  $S$ , gives the Green's function between the two receivers – one of the receiver is transformed into a virtual source. **b.** Using reciprocity, the Green's function can be approximated between two sources located at  $x_1$  and  $x_2$ , cross correlating signals recorded on a surface  $S$ . **c.** It can be shown that most of the reconstruction of the Green's function can be achieved using signals recorded along the  $x_1$ - $x_2$  line (grey areas) (after Curtis et al., 2009).



**Figure 2:** Comparison of seismograms for earthquake 1 recorded by the normal virtual receiver 4 (solid line) with the directly recorded radial component measurements from seismometer R06C (dashed line). Virtual seismometer records are constructed using 15 stations from the USArray and Berkeley seismic network (after Curtis et al., 2009).

Note that an earthquake source acts like a double couple, so by reciprocity, **the virtual seismometer acts like a strain recorder**, contrary to classical seismometers which record ground displacement or velocity. Considering two earthquakes characterized by two moment tensors  $M^1$  and  $M^2$ , and respective source time function  $S_1$  and  $S_2$ , Curtis et al. (2009) derive the resulting interferometric Green's function as follow (in the frequency domain)

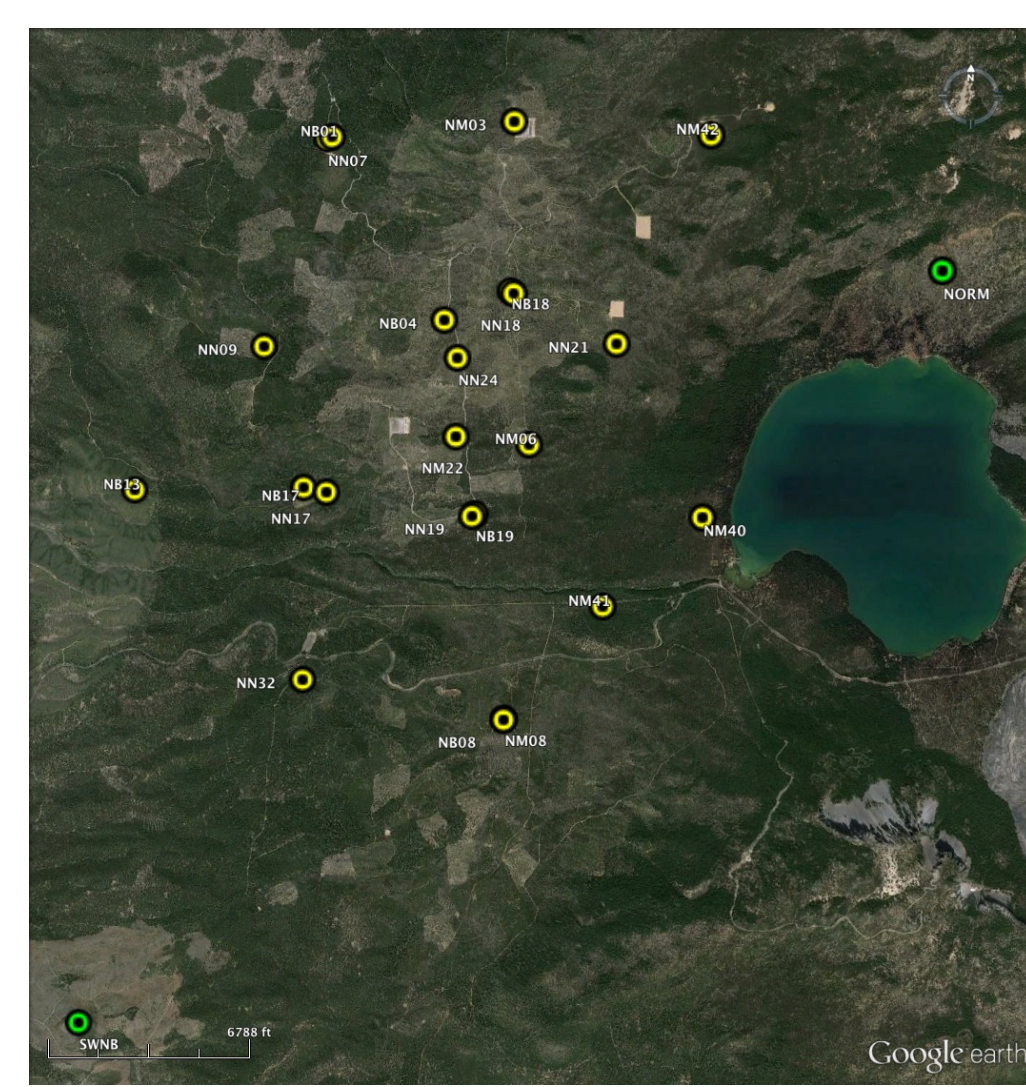
$$S_2 S_1^* M_{ip}^2 M_{mq}^1 \partial_p \partial_q G_{im}^h(x_2, x_1) = \int [u_n(x_2, x) T_n^*(x_1, x) - T_n(x_2, x) u_n^*(x_1, x, -t)] d^2 x \quad (1)$$

which requires both monopole and dipole recordings of energy from both moment tensor sources. As we can only access particle-displacement seismometers, this expression can further be approximated to

$$S_2 S_1^* M_{ip}^2 M_{mq}^1 \partial_p \partial_q G_{im}^h(x_2, x_1) \sim i K \omega \int u_n(x_2, x) u_n^*(x_1, x) d^2 x \quad (2)$$

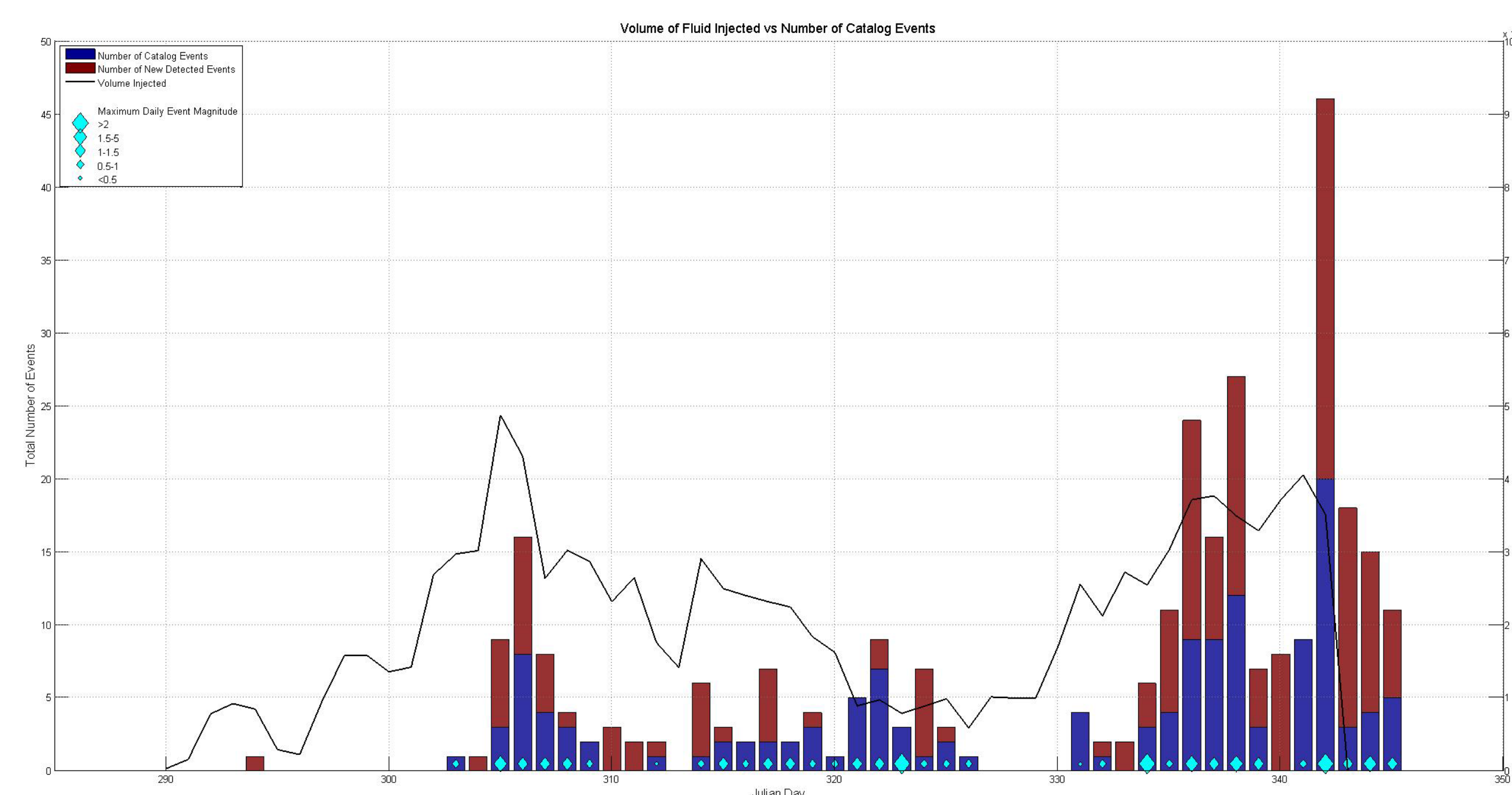
## Microseismicity at the Newberry EGS site

AltaRock Energy Inc. injected water into Well NWG 55-29 at the Newberry Volcano, Oregon, October 17 - December 7, 2012 (Fig. 3). The objective of the project was **to create by hydraulic injection a fracture network** in the hot rock penetrated by the well. Ultimately, a second (production) well will be drilled to intersect the fracture network created. Water will be circulated through the fracture network where it will heat up, and be extracted via the production well and used to generate electricity.



**Figure 3:** Map of the Newberry experiment network.

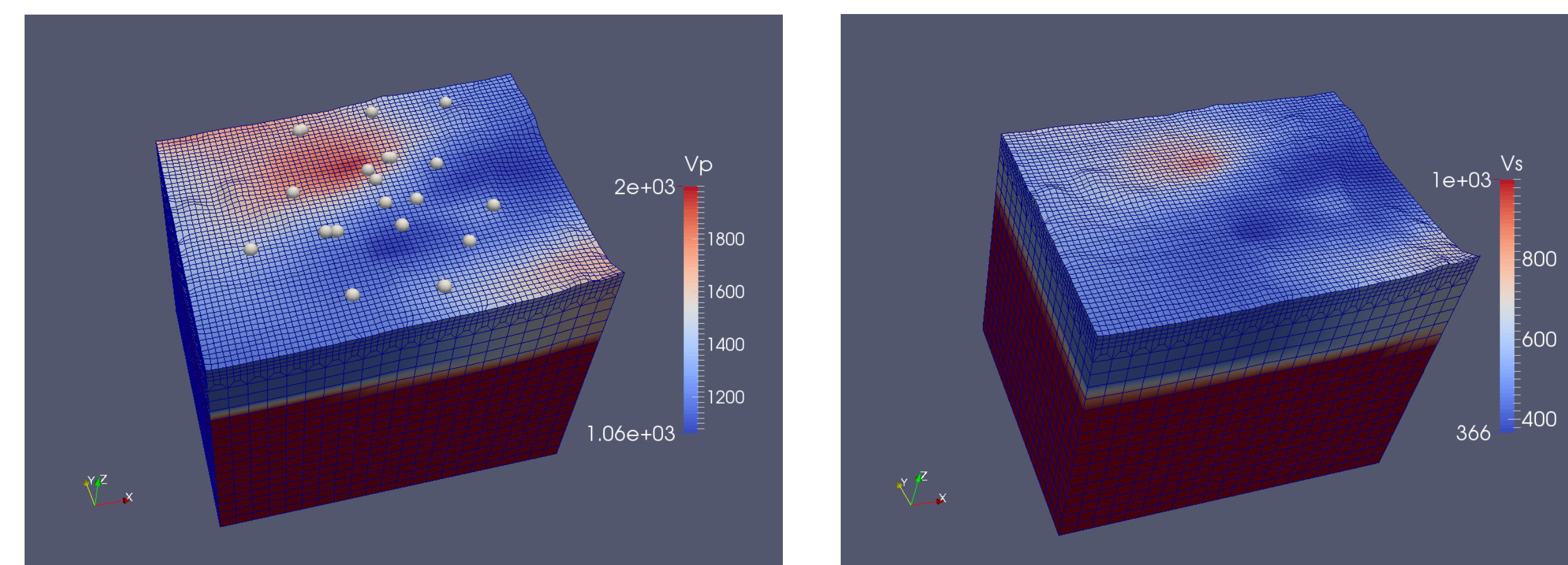
In order to site the production well as advantageously as possible, it is **necessary to know the location and nature of the fracture network created**. It is also important **to identify faults at risk of slipping**. This information can only be obtained by studying the micro earthquakes triggered by the hydraulic injection (Figs. 4 & 5).



**Figure 5:** Comparison of event rate (original catalogue from AltaRock Energy Inc. and improved detection using Bayesloc) and fluid injected.

## Model Setup

We use a spectral-element code, SPECFEM3D, which calculates full wave propagation, and apply it to a 3D model of the Newberry site (Fig. 6).



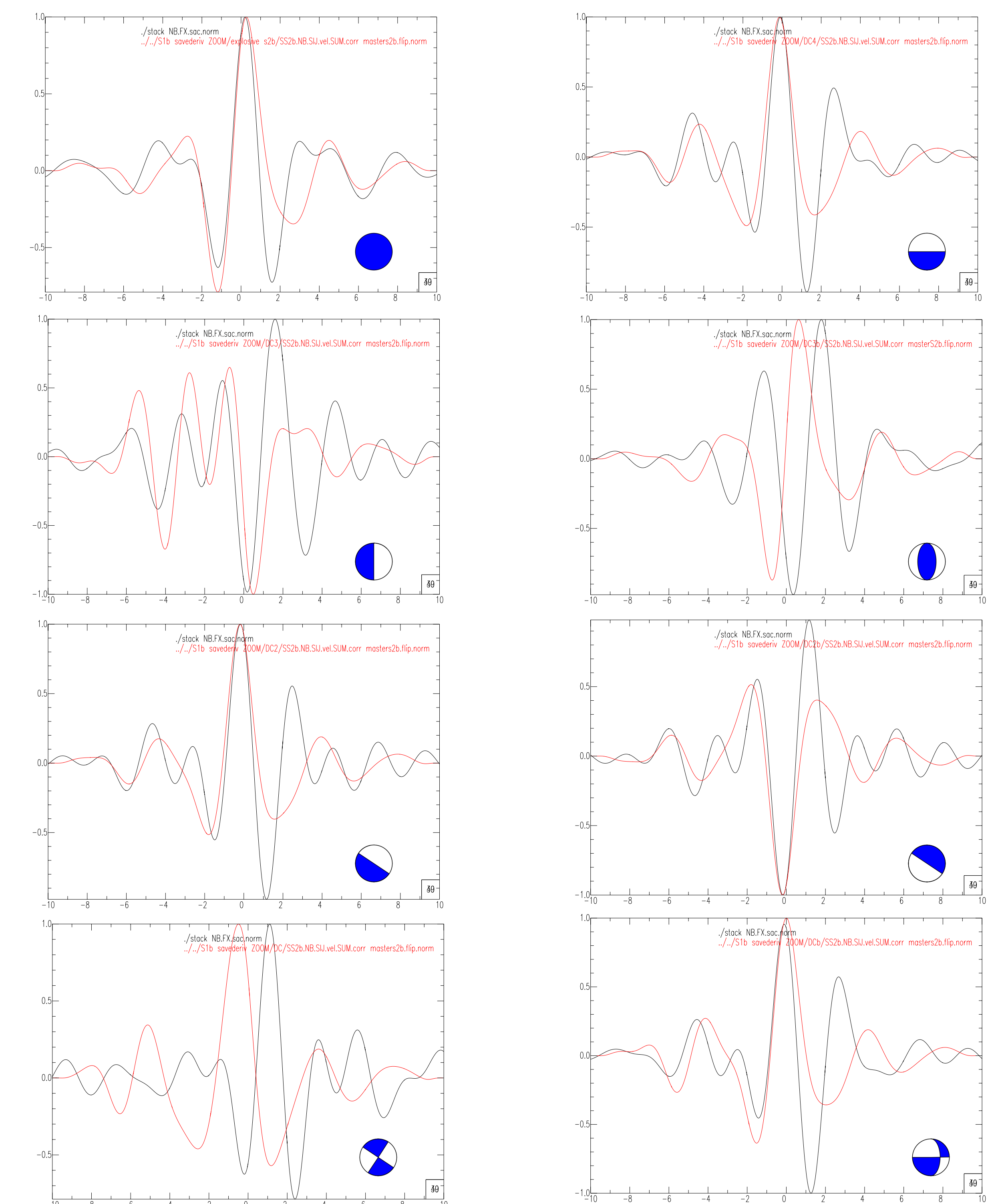
**Figure 6:** 3D model of Newberry, showing the refined mesh, the  $V_p$  and  $V_s$  models derived by ambient noise tomography by Eric Matzel. The model extends to 5km depth and includes topography. The white spheres represent the location of the stations.

An isotropic master source is located at 1.5 km depth. This master is recorded by virtual seismometers, which are constructed from a series of micro earthquakes with varying focal mechanisms. Each of these virtual seismometers is located 500 m above the master.

1. We record the ground motion generated by the master event and the secondary events at each station.
2. We cross correlate master and secondary waveforms recorded at each station.

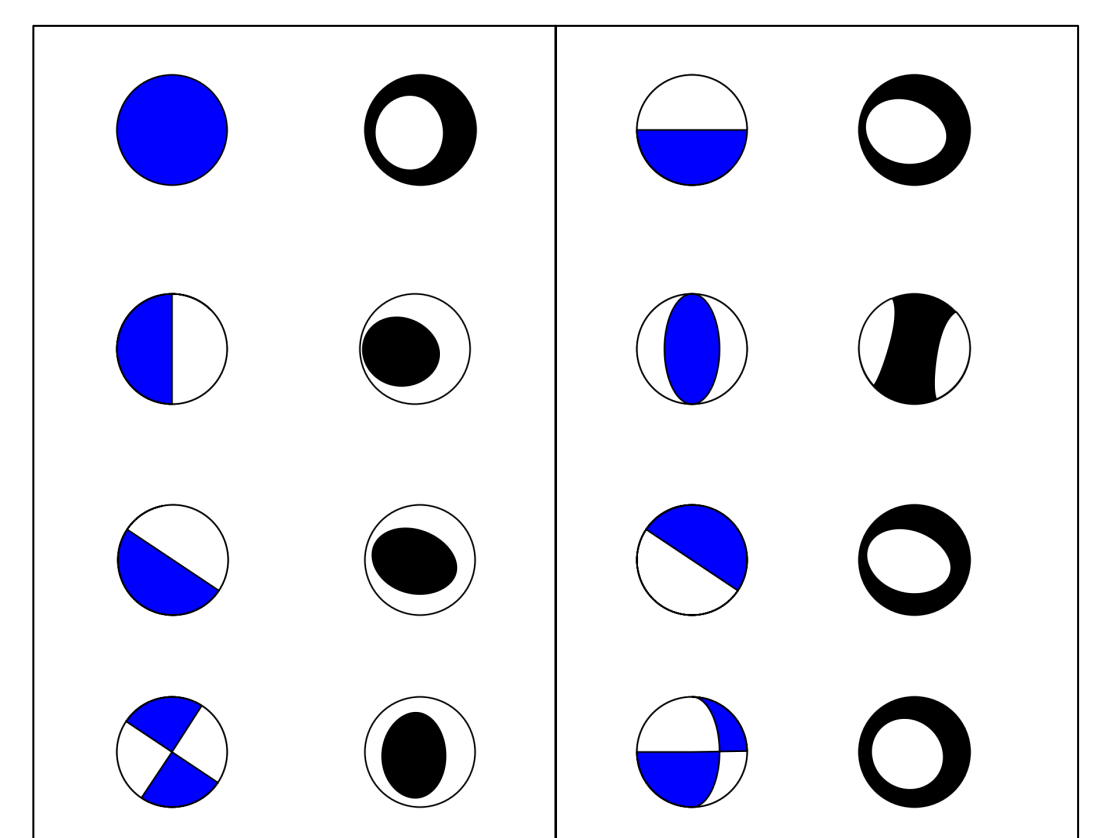
## Results

Using equation (2), we show that **VSM directly recovers the waveform between the two events** (Fig. 7).



**Figure 7:** The VSM Green's function estimates (black curve) compared to the actual Green's function (red curve), for a variety of focal mechanisms (blue focal mechanism). All waveforms are filtered between 2-5s.

**Using the waveforms generated by VSM, we show the potential of recovering the focal mechanism of the secondary events** (Fig. 8). Discrepancies are related to the geometry between the two micro earthquakes and the recording network. An other aspect is also to improve the inversion algorithm, and to possibly increase the number of master events to provide a complete coverage of the focal sphere.



**Figure 8:** Comparison between known focal mechanisms of the secondary sources (blue) and inverted focal mechanism using VSM waveforms (black).

## Conclusions – Future Work

- VSM works by effectively replacing each micro earthquake with a virtual seismometer.
- We show that we can recover waveforms between two micro earthquakes using recorded signals at the surface in complex heterogeneous media. This signal can be used to invert for the focal mechanism.
- Since this inversion implies that one source is exactly known, which can be hard to achieve in practice, we are also investigating a new algorithm to track relative difference between two focal mechanisms, which by itself can be indicative of different fracture openings.
- Next, we will employ this approach using recorded micro events at geothermal sites (e.g., Newberry in the US, Basel in Switzerland).

## References

- Campillo, M., and A. Paul, 2003. Long-range correlations in the diffuse seismic coda, *Science*, 299, 547–549
- Curtis, A., H. Nicolson, D. Halliday, J. Trampert, and B. Baptie, 2009. Virtual seismometers in the subsurface of the earth from seismic interferometry, *Nature Geoscience*, 2, 700–704
- Templeton, D., G. Johannesson, and S.C. Myers, 2014. An investigation of the microseismicity at the Newberry EGS site, *35 Workshop on Geothermal Reservoir Engineering*, Stanford, CA